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Quality Control of Meteorological Observations

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Foreword

Meteorological observations are subjected to extensive objective quality control prior to storage in an operational atmospheric data base at the Fleet Numerical Oceanography Center (FNOC). The quality-controlled observations are used by the Navy's global and regional atmospheric prediction models and by the stratospheric analysis. The atmospheric analyses and models produce numerical guidance and products in support of a wide range of Navy atmospheric and oceanographic requirements. Quality control of the meteorological observations is for identifying and eliminating erroneous observations that can adversely affect the quality of these operational products. The objective quality control of the meteorological observations is described in this report. Details pertaining to the actual implementation of the quality control system at FNOC are described in NOARL Report 25.

Because of the potentially serious impact of erroneous observations on meteorological applications and products, quality control is necessary for all unprocessed observations. In addition, quality-control procedures rarely are documented in sufficient detail. Therefore, this report will be of interest not only to users of the operational atmospheric data base, but also to those who need to develop quality-control systems for independent applications. It will also be of interest to users of the data provided by the Naval Postgraduate School in support of the Tropical Cyclone Motion (TCM-90) experiment, since the observations retrieved from the atmospheric data base were quality controlled by these methods.

The quality control procedures were initially developed in support of the Navy Operational Global Atmospheric Prediction System (NOGAPS) and in direct response to the validated Chief of Naval Operations requirements LANT MET 77-15 and OR 072-006-86. Because of the need for quality-controlled observations, other operational products now access the data base. All these products will continue to benefit from the ongoing development of quality control techniques.

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Executive Summary

Quality control of meteorological observations is an integral part of atmospheric analysis and prediction, since erroneous observations can adversely impact the accuracy of these environmental products. The meteorological observations are subjected to various validation and error checks, as described in this report, prior to their storage in an operational atmospheric data base at the Fleet Numerical Oceanography Center (FNOC). The operational atmospheric data base is used by the Navy's global and regional prediction systems and by the stratospheric analysis. These models provide direct environmental support for fleet operations worldwide. The same quality control procedures were also used for the preliminary error checking of many of the observations gathered during the TCM-90 (Tropical Cyclone Motion) experiment. This initiative, sponsored by the Office of Naval Research, was one component of several joint experiments conducted in the tropical western Pacific Ocean during the summer of 1990.

The observations that are processed are from a variety of sources. Each observing platform has its own unique error characteristics, which must be taken into consideration. These sources include observations of pressure, wind and temperature from ships, fixed and drifting buoys, and land stations. Satellite-based instruments infer atmospheric temperature and moisture profiles, tropospheric wind velocity, and sea-surface wind speeds. Commercial aircraft report air temperature and wind velocity. Perhaps the most important source of information comes from radiosonde and pilot balloon observations of upper atmosphere temperature, moisture, and wind velocity profiles. The quality checking procedures for these observations are derived from a series of rules. Many of the rules are based upon geophysical limitations, such as checks against extreme observed values and checks for hydrostatic consistency. Other rules stem from required reporting practices. After the quality tests are finished, flags are set for each observation within a report, indicating its assessed quality.

This report describes the quality control of the meteorological observations in the atmospheric data base in sufficient detail to acquaint users of the data of the level of error checking performed prior to storage in the operational atmospheric data base. The majority of the quality checks are sufficiently general so that they could be used for other applications and observation types. Although these checks apply only to meteorological observations, the same techniques should work for some oceanographic observations as well.

Acknowledgments

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Quality Control of Meteorological Observations

1.0 Introduction

The Navy's current operational atmospheric data base (ADPFNOC) was originally developed to provide quality-controlled observations in a format acceptable for the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan et al., 1991). The data base and quality control (QC) procedures were developed by the Atmospheric Directorate of the Naval Oceanographic and Atmospheric Research Laboratory in coordination with the Fleet Numerical Oceanography Center (FNOC). The quality checking and flagging procedures for this data base were specifically designed for use by NOGAPS. The regional models, stratospheric analysis and several other operational products now access the same data base (Goerss and Phoebus, 1991). However, only the NOGAPS multivariate optimum interpolation (MVOI) analysis and its related support programs are allowed to set the analysis quality flags associated with the observations in the data base.

The QC of meteorological observations for the operational atmospheric data base consists of four main components. These four components are preanalysis objective quality checks, checks within the analysis for consistency against the background and neighboring observations, subjective evaluation of marine observations, and the determination and correction of observational biases, such as the radiative errors of radiosondes. To provide integrated QC, the development and implementation of these four components must be coordinated. Ideally, no final QC decision would be made until all validation checks had been made. Then, the results of each test would be examined and a final decision made. This is the basic premise of Complex Quality Control (CQC), as described by Gandin (1988). The development of the QC procedures discussed in this report was coordinated, but quality decisions are made during each individual step.

This report describes in detail the preanalysis objective QC. The subsequent checks against the analysis background and for consistency with surrounding observations made in the analysis are discussed by Goerss and Phoebus (1991). The details pertaining directly to the implementation of the QC system at FNOC are presented in Baker (1991). These details include the data base structure and data formats, manual QC procedures, and the statistical data base and methods used for the identification and correction of observational basis.

2.0 Objective Quality Control

The first step is the preanalysis objective QC. The QC procedures were adapted from those in use operationally at the European Center for Medium-Range Weather Forecasting (ECMWF) (Norris, 1991) and are similar to those in use at other operational centers worldwide. Some of the quality checks within this stage are based upon geophysical constraints, such as hydrostatic balance, lapse rate limitations, and climatological limits. Others evaluate the internal consistency of the report. Still others are based upon rules established by the World

Meteorological Organization (WMO) for the exchange of meteorological observations (WMO, 1988). An example of the latter are the rules governing the selection of significant levels on a rawinsonde report.

Each observation within a report (e.g., temperature or height) has a QC flag assigned according to First GARP* Global Experiment (FGGE) specifications. The QC procedures described by Norris (1991) use four degrees of confidence, while the FGGE format allows only three. Four levels of confidence are used internally within the QC algorithms and are converted to FGGE confidence flags in accordance with Table 1.

Table 1. Flag definitions.

INTERNAL FLAG	FGGE FLAG
0: Value Correct	0: QC Not Done
1: Probably Correct	1: Good
2: Probably Wrong	2: Suspect
3: Value Wrong	3: Bad

Unless otherwise noted, counters associated with each observation within the report are incremented each time a test is failed. A "trivial" error increments the counter by 1, a "fatal" error increments the counter by 4. At the end of all the tests, 1 is deducted from each counter (greater than 1), and the QC flag is set equal to that value, subject to a maximum value of three. This yields the ECMWF-type QC flag, which is converted to a FGGE-type flag at the end of the quality checking as indicated in Table 1. In some cases, erroneous values may be replaced by likely substitutions. Then, original value is flagged as rejected and retained.

The parameters listed in the following sections are in standard WMO notation. The reader is referred to WMO (1988) for parameter definitions and code tables. The severity of an error is indicated with T = trivial, S = serious, and F = fatal.

2.1 Surface Reports

All observations are checked against plausibility or gross error limits. The gross error tolerances are set slightly greater or smaller than the record observed maximum or minimum values for a parameter. For example, the minimum and maximum plausibility limits for land temperatures are –90°C and 60°C, respectively. Historically, the minimum recorded temperature was –89°C at Vostok, Antarctica, and the maximum recorded temperature was 58°C at El Azizia, Libya (Riordan and Bourget, 1985). At the present time, the plausibility limits do not vary with seasons. The observations are also checked for internal consistency. An example of a violation of internal consistency would be a station reporting variable wind direction and a windspeed greater than 6 msec^{-1}.

No substitutions are provided for erroneous surface data except for ship position, which may be corrected as a result of the operational ship-tracking program at FNOC. Based upon its previously reported positions, the allowable region for a ship's location is calculated. Ships that report a position outside this region may have their positions corrected, or the ship position QC flag is set to reject. The new position must resemble the position originally reported, i.e., 25.2°N, 130.0°E could be replaced with 25.2°N, 130.0°W. The reports are subjectively evaluated if only two reports from the same ship are available and they are in disagreement and cannot be corrected as in the above example.

*Global Atmospheric Research Program.

Table 2. Minimum and maximum permitted pressure or height values for surface date given pressure level indicator. A "*" indicates that the value is not checked against limits.

FGGE PRESSURE CODE INDICATOR	MINIMUM (*ppp* OR *HHHH*)	MAXIMUM (*ppp* or *HHHH*)
0 (*ppp* = Sea Level)	880 mb	1080 mb
1 (*ppp* = Station Level)	*	*
6 (*HHHH* = 850 mb)	250 m	2100 m
7 (*HHHH* = 700 mb)	1600 m	3800 m
8 (*HHHH* = 500 mb)	3800 m	6600 m
9 Type Unknown	*	*

The quality checks for surface data are as follows:

Pressure and geopotential height *ppp*, *HHHH*

Ship only: pressure level code $\neq 0$ .... F
Ship only: $ppp < 880$ or $ppp > 1080$ mb .... F
Land only: $ppp < ppp_{min}$ or $ppp > ppp_{max}$ .... F
Land only: $HHHH < HHHH_{min}$ or $HHHH > HHHH_{max}$ .... F
where the pressure and height limits depend upon pressure level code indicator and are given in Table 2.

Wind direction and speed *dd*, *FF*

$dd < 0$ or $dd > 360$ and dd not variable .... F
dd missing, FF not missing .... T
dd not missing, FF missing .... T
$dd = 0$, $FF \neq 0$ .... F
$dd \neq 0$, $FF = 0$ .... F
dd = variable, $FF > 3$ msec^{-1} .... T
dd = variable, $FF > 6$ msec^{-1} .... F
$FF \geq 45$ msec^{-1} .... F

Air temperature and dewpoint *TT*, T_dT_d

$TT < -90°C$ or $TT > 60°C$ .... F
$T_dT_d < -90°C$ or $T_dT_d > 60°C$ .... F
$TT > T_dT_d + 1°C$ and $42 \leq ww \leq 49$ .... T
$TT < -2°C$ and $50 \leq ww \geq 55$ or $58 \leq ww \leq 65$
or $68 \leq ww \leq 69$ or $80 \leq ww \leq 82$ .... T
$TT > 6°C$ and $68 \leq ww \leq 79$ or $83 \leq ww \leq 88$ .... T
Land only: $TT < T_dT_d$ .... T
Land only: $TT - T_dT_d > 50°C$ .... T
Ship only: $TT < T_dT_d - 1°C$ .... T
Ship only: $TT - T_dT_d > 30°C$ .... T

Pressure tendency and magnitude *a*, *pp*

$pp = 0$ and $a \neq 0$, 4, or 5 .... T
$a = 4$ and $pp \neq 0$ .... T
$pp < -40$ mb or $pp > 40$ mb .... F

Seasurface temperature T_wT_w

$T_wT_w < -2°C$ or $T_wT_w > 40°C$ .... F

Table 3. Maximum and minimum temperatures allowed (given height) for aircraft data.

HHH (m)	TT_{min}(°C)	TT_{max}(°C)
$9900 \le HHH$	−100	60
$7800 \le HHH < 9900$	−100	0
$6100 \le HHH < 7800$	−90	5
$4700 \le HHH < 6100$	−90	13
$3270 \le HHH < 4700$	−90	20
$2280 \le HHH < 3270$	−90	27
$1500 \le HHH < 2280$	−90	34
$HHH < 1500$	−90	60

Table 4. Maximum permitted windspeeds for aircraft data.

HHH (m)	FF_{max} (msec^{-1})
$12000 \le HHH$	130
$9000 \le HHH < 12000$	154
$5500 \le HHH < 9000$	128
$3000 \le HHH < 5500$	103
$1500 \le HHH < 3000$	70
$1200 \le HHH < 1500$	65
$HHH < 1200$	60

2.2 Aircraft Reports

All observations are checked against climatological limits, as well as for internal consistency. No substitutions are provided for erroneous observations.

The quality tests for aircraft observations are listed:

Geopotential height *HHH*

$HHH < 10$ m or $HHH > 25.000$ m .... F

Air temperature *TT*

$TT < TT_{min}$ or $TT > TT_{max}$ or HHH already flagged 3 .... F

where TT_{min} and TT_{max} depend on HHH and are given in Table 3.

Wind direction and speed *dd, FF*

dd missing, FF not missing .... T

dd not missing, FF missing .... T

$dd < 0$ or $dd > 360$ and dd not variable .... F

$dd = 0$, $FF \neq 0$ .... F

$dd \neq 0$, $FF = 0$ .... F

dd variable and $FF > 3$ msec^{-1} .... T

dd variable and $FF > 6$ msec^{-1} .... F

dd and FF present but HHH already flagged 3 .... F

$FF > FF_{max}$ .... F

$FF > 0.8\ FF_{max}$ .... S

where FF_{max} is given by Table 4.

2.3 Satellite Cloud-Tracked Winds

All observations are checked against climatological limits, as well as for internal consistency. No substitutions are provided for incorrect observations.

For satellite cloud-tracked winds, the error checks are:

Atmospheric pressure *ppp*

$ppp < 0$ or $ppp > 1080$ mb .... F

Wind direction and speed *dd, FF*

dd missing, FF not missing .... T

dd not missing, FF missing .... T

$dd < 0$ or $dd > 360$ and dd not variable .... F

$dd = 0$, $FF \neq 0$ .... F

$dd \neq 0$, $FF = 0$ .... F

$FF > FF_{max}$ .... F

$FF > 0.8\ FF_{max}$ .... S

Table 5. Maximum and minimum temperatures and wind speed tolerances for satellite cloud-tracked winds.

ppp (mb)	TT_{min}(°C)	TT_{max}(°C)	FF_{max}(msec^{-1})
$ppp < 200$	−100	0	130
$200 \le ppp < 400$	−100	0	154
$400 \le ppp < 500$	−90	5	128
$500 \le ppp < 600$	−90	13	103
$600 \le ppp < 700$	−90	20	103
$700 \le ppp < 800$	−90	27	70
$800 \le ppp < 850$	−90	34	70
$850 \le ppp < 900$	−90	34	65
$1000 \le ppp < 1080$	−90	60	60

Table 6. Maximum and minimum temperatures for satellite soundings.

ppp (mb)	TT_{min}(°C)	TT_{max}(°C)
$ppp < 100$	−100	0
$100 \le ppp < 200$	−100	0
$200 \le ppp < 300$	−100	0
$300 \le ppp < 400$	−100	0
$400 \le ppp < 500$	−90	5
$500 \le ppp < 600$	−90	13
$600 \le ppp < 700$	−90	20
$700 \le ppp < 800$	−90	27
$800 \le ppp < 900$	−90	34
$900 \le ppp < 1000$	−90	60
$1000 \le ppp < 1100$	−90	60

Temperature TT

$TT < TT_{min}$ or $TT > TT_{max}$ .... F

where FF_{max}, TT_{min} and TT_{max} depend upon ppp and are given by Table 5.

2.4 Satellite Soundings

All observations are checked against climatological limits, as well as for internal consistency. For satellite soundings, the individual levels are not flagged. Rather, the entire sounding retains an overall quality flag. Any error in the precipitable water results in a FGGE quality flag of "suspect"; any error in temperature or thickness results in a quality flag of "bad." The majority of the errors caught by the objective QC are errors introduced by the data decoders. No substitutions are provided for erroneous data.

For each level of the satellite sounding, the QC checks are:

Base pressure $p_ap_a < 0$ or $p_ap_a > 1080$ mb .... F

Upper pressure $p_ip_i < 0$ or $p_ip_i > 1080$ mb .... F

Mean temperature $\overline{TT} < \overline{TT}_{min}$ or $\overline{TT} > \overline{TT}_{max}$ .... F

Precipitable water $www < 0$ or $www > www_{max}$ .... F

Thickness $t_lt_lt_l \le 0.5\ \underline{t_lt_lt}_{lmax}$ or $t_lt_lt_l > t_lt_lt_{lmax}$ .... F

In the above tests, $\overline{TT}_{min}$ is the mean of the minimum temperatures for $p_ap_a, p_ap_a + 100, \ldots, p_i\,p_i - 100$ as given by Table 6. The value

Table 7. Maximum permitted thicknesses and precipitable water for layers between standard pressure levels.

LAYER (mb)	THICKNESS $t_l t_l t_{l\,max}$ (m)	PRECIPITABLE WATER www_{max} (mm)
1000 – 850	1541	106
850 – 700	1718	36
700 – 500	2884	27
500 – 400	1880	20
400 – 300	2382	15
300 – 250	1509	9
250 – 200	1847	4
200 – 150	2382	0
150 – 100	3357	0
100 – 70	2953	0
70 – 50	2786	0
59 – 30	4229	0
30 – 20	3357	0
20 – 10	5739	0
10 – 7	3057	0
7 – 3	7263	0
3 – 1	9739	0

$\overline{TT}_{max}$ is computed similarly. Precipitable water is calculated assuming saturation at the maximum allowed temperatures. The value www_{max} is given by Table 7 and is summed between the base pressure and upper pressure. Pressures (and corresponding precipitable water values) at nonstandard pressure levels are interpolated. The thicknesses are computed from the hypsometric equation, where $t_l t_l t_{l\,max}$ is the sum of the thickness between the base and upper levels given in Table 7. Nonstandard level pressures and thicknesses are interpolated.

2.5 Radiosonde Observations

Radiosonde observations determine the vertical temperature and humidity profiles of the atmosphere as a function of pressure. A rawinsonde report includes wind velocity measurements as well. The terms radiosonde and rawinsonde are used interchangeably within this report. Radiosondes are probably the single most important observation source available. For this reason, the most effort is expended on them, and they are discussed in greater detail here.

A radiosonde consists of an instrument package suspended from a helium-filled balloon, which is released into the atmosphere. The temperature is measured by a thermistor, the humidity by a hygristor, and the pressure by an aneroid cell. As the pressure cell expands, a stylus is dragged across contact points, and the data are transmitted back via radio to the ground receiving station. Observations of wind direction and speed are determined by the displacement of the balloon from the launch point. With a rawinsonde, the tracking is done electronically. Pilot balloons, or PIBALS, are measurements of windspeed and direction only, as a function of height and/or pressure, with the tracking done optically. The FNOC and WMO (1990) master station lists indicate which procedure is in use at a given station.

The WMO has established rules for the international exchange of radiosonde observations. Specific criteria apply to the selection of mandatory and significant levels in a radiosonde observation. For example, all stations must report mandatory level information. In addition, a sufficient number of significant levels must be selected so that the reported sounding reproduces the recorded sounding trace to within certain limits. Requirements also exist for the delineation of significant inversions. These rules provide the basis for the radiosonde quality checks of this section.

The QC procedures closely follow those in use at the ECMWF (Norris, 1990). The order in which these checks are performed is critical because a decision must be made whether an observation that is flagged as suspect or bad by a particular check will be considered further. Data that is rejected by one check may be validated by a later check, or it may erroneously allow adjacent observations to be rejected. The quality flags for each observation are set directly by the individual tests (as opposed to a system of counters) so that the QC flags reflect the most recent quality assessment. In general, the checks proceed from crude to more refined so that obvious errors are eliminated early on. The priority is on the validation of the mandatory levels, since they are the primary ones used by the analyses. Substitutions may be provided for erroneous observations, but in all cases, the original is retained with a flag of "reject." In general, substitutions suggested by one step replace only data flagged as rejected by a prior step.

The tests below refer to the radiosonde observations parts A, B, C, and D. The mandatory and significant level below 100 hPa are contained in parts A and B, respectively. The mandatory and significant level data above 100 hPa are contained in parts C and D, respectively.

The radiosonde vertical consistency test proceeds in the following order:

1. Start the vertical QC of one observation; all the available parts of the message are used.
2. Compare all values in the observation against climatological limits (section 2.5.1).
3. Check the lapse rate of the vertical temperature profile (section 2.5.2).
4. If parts B and/or D are available, then recompute the standard level data from the significant level data. Compare the reported standard pressure level data with the recomputed data. Adjust, if possible, the reported standard pressure level data (section 2.5.3).
5. Check for hydrostatic consistency between standard pressure levels (section 2.5.4).
6. Check for excessive wind shear control (section 2.5.5)
7. Vertical QC is finished.

2.5.1 Climatological Limits Checks

All observations are compared against climatological or gross error limits. The limits represent the maximum observed values for each observation. At the present time, these values are fixed and do not vary with season or latitude. The climatological limits for radiosonde observations are presented in Tables 8 through 11.

Table 8. Climatological limit checks where TT_{min} and TT_{max} depend on *ppp* and are given by Table 10, and where FF_{max} depends upon *ppp* if present, otherwise on *HHH* and is given by Table 11.

SURFACE LEVEL	RANGE	FLAG
Atmospheric Pressure	$ppp > 1080$ mb	2
Air Temperature	$TT < -90°C$ or $TT > 60°C$	2
Windspeed	$FF > 45$ msec^{-1}	2
UPPER LEVEL	**RANGE**	**FLAG**
Temperature	$TT < TT_{min}$ or $TT > TT_{max}$	3
Dewpoint	$TT - T_dT_d < -1°C$ or $TT - T_dT_d > 50°C$	3
Windspeed	$FF > 0.8\ FF_{max}$	2
	$FF > FF_{max}$	3

Table 9. Maximum and minimum permitted heights for radiosonde mandatory pressure levels.

LEVEL (mb)	MINIMUM HEIGHT (m)	MAXIMUM HEIGHT (m)
1000	-350	400
850	900	1700
700	2400	3400
500	4400	6200
400	6000	7700
300	7700	10000
250	9000	11200
200	9900	12800
150	12000	14600
100	14500	17000
<100	15000	35000

Table 10. Maximum and minimum permitted temperatures for various levels of the atmosphere.

ppp (mb)	TT_{min} (°C)	TT_{max} (°C)
$ppp < 300$	-100	0
$300 \le ppp < 400$	-100	0
$400 \le ppp < 500$	-90	5
$500 \le ppp < 600$	-90	13
$600 \le ppp < 700$	-90	20
$700 \le ppp < 800$	-90	27
$800 \le ppp < 900$	-90	34
$900 \le ppp < 1080$	-90	60

Table 11. Maximum permitted windspeeds for various levels.

ppp (mb)	*HHH* (m)	FF_{max} (msec^{-1})
$ppp < 50$	$22000 < HHH$	160
$50 \le ppp < 200$	$12000 < HHH \le 22000$	160
$200 \le ppp < 400$	$6500 < HHH \le 12000$	160
$400 \le ppp < 500$	$5500 < HHH \le 6500$	128
$500 \le ppp < 700$	$3000 < HHH \le 5500$	103
$700 \le ppp < 850$	$1500 < HHH \le 3000$	70
$850 \le ppp < 1000$	$500 < HHH \le 1500$	65
$1000 \le ppp$	$HHH \le 500$	65

2.5.2 Lapse Rate Checks of Vertical Temperature Profiles

Lapse rate QC checks the vertical temperature profile in the sounding for unreasonable lapse rates. The sounding is scanned layer by layer from the surface to the highest level. All mandatory and significant level temperature data are used. The lapse rate is allowed to be slightly superadiabatic. Extreme inversions are not permitted. If an unlikely lapse rate is detected, an attempt is made to determine which temperature is in error by examining the adjacent layers. If the error can be isolated, a change of sign for that temperature is tested and a substitution provided if appropriate. This test is valuable for detecting and correcting sign errors. For each layer the following procedure is applied:

1. Use the temperature T_i at pressure p_i to extrapolate a new temperature T'_{i+1} at the pressure level p_{i+1} by the dry adiabatic lapse rate.

$$[T'_{i+1} = T_i \ (p_{i+1}/p_i)^{R/C_p}] \,. \tag{1}$$

2. Compare the computed temperature T'_{i+1} with the reported temperature T_{i+1}. If $T_{i+1} \geq T'_{i+1}$ for $p_i \leq 500$ hPa or $T_{i+1} \geq T'_{i+1} - 1$ for $p_i > 500$ hPa, then the temperature profile (T_i, T_{i+1}) is not considered to be superadiabatic, and the checking procedure continues on to the next layer. However, if the above is not satisfied, at least one of the reported temperatures T_i or T_{i+1} must be erroneous. To determine which temperature is erroneous and correct the error if possible, it is necessary to use adjacent level data. The following algorithms are applied:

(a) If $[T_{i+1} < T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} \geq T_i \ (p_{i+2}/p_i)^{R/C_p}]$, then the temperature T_{i+1} is marked as "erroneous," *Flag = 3.*

(b) If $[T_{i+1} \geq T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} < T_i \ (p_{i+2}/p_i)^{R/C_p}]$, then the temperature T_i is marked as "erroneous," *Flag = 3.*

(c) If $[T_{i+1} > T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} > T_i \ (p_{i+2}/p_i)^{R/C_p}]$, then the adjacent mandatory pressure level data is used to determine the error. The thickness between adjacent mandatory levels from the two profiles $(\ldots, T_{i-1}, T_{i+1}, T_{i+2} \ldots)$, and $(\ldots, T_{i-1}, T_i, T_{i+2} \ldots)$ are computed. The profile that has a thickness that deviates the most from the reported thickness is considered in error and the corresponding T_i or T_{i+1} is marked as bad, *Flag = 3.*

(d) If $[T_{i+1} < T_{i-1}(p_{i+1}/p_{i-1})^{R/C_p}]$ and $[T_{i+2} < T_i \ (p_{i+2}/p_i)^{R/C_p}]$, then it is not sufficient to delete one of the temperatures T_i or T_{i+1} to get a profile that is not superadiabatic. Since this is an unlikely event and further testing is too complex, the check terminates and the flags for T_i and T_{i+1} are set to *Flag = 2.*

(e) For all other possible combinations, no definite conclusions can be drawn, and the *flags are incremented by 1, subject to a maximum value of 3* for both T_i and T_{i+1}.

(f) If an "error-marked" temperature would become correct according to lapse-rate control just by changing its sign, then this change will be made and the *flag of the original set to 3.*

2.5.3 Consistency Between Mandatory and Significant Levels

The WMO (1988) reporting regulations require that a sounding must be reproducible to within specified limits from the significant level data alone. This redundancy of information gives an additional check on the reported mandatory pressure level data. In this step, the standard pressure level data are recomputed from the significant level data and compared with the reported standard pressure level data. The tolerances for the tests are given in Table 12. The adjacent significant levels must be within 100 mb of the mandatory level, and the mandatory level must not be tagged as significant. In addition, this check is not used for

Table 12. Limits for deviations for computed and reported standard pressure level data.

PARAMETER	LEVEL	LIMIT
Height	Height > 6000 gpm	30 gpm
Height	Height > 600 gpm	20 gpm
Temperature	Below Tropopause and Below 300 mb	1.5 °C
Temperature	Above Tropopause or Above 300 mb	3.0 °C
Dewpoint Temperature		10.0 °C
Windspeed		25 $msec^{-1}$
Wind Direction	$FF \leq 5$ $msec^{-1}$ No Limit, $FF > 5$ $msec^{-1}$	50°

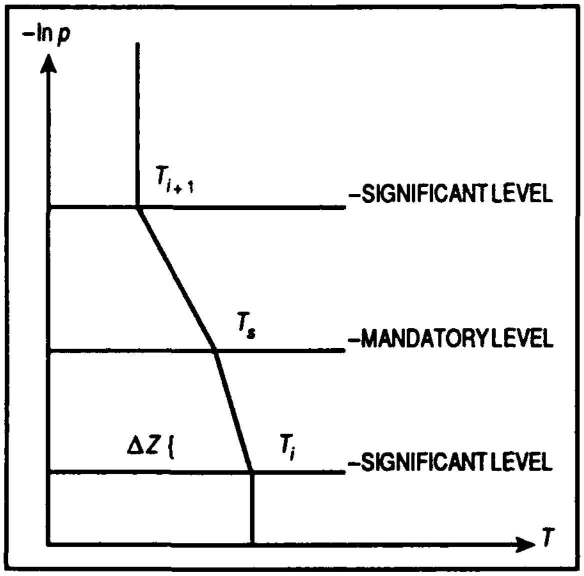

Figure 1. Temperature profile schematic of significant and mandatory pressure levels.

dewpoint depression if the dewpoint depression falls below 30°C at the level under consideration. When possible, substitutions are provided for data previously determined to be in error. In practice, this procedure works quite well for temperatures and reasonably well for winds. The procedure is inadequate for humidity because there is no distinction made between a significant level selected for temperature as opposed to humidity. The requirements for log-linearity still apply, but seem to be less stringently adhered to for humidity data. Regional coding practices (as with the United States rawinsondes) sometimes dictate that the significant level wind information be transmitted independently in the PIBAL format (WMO, 1972). Since radiosonde and PIBAL reports are not combined, this check cannot be used for these stations.

The checking procedure proceeds as follows:

1. Temperature and dewpoints are interpolated to the standard pressure levels assuming a linear variation in (ln p) between the significant levels as shown in Figure 1. For example,

$$T_s = T_i + \frac{\ln\left(\frac{p_s}{p_i}\right)}{\ln\left(\frac{p_{i+1}}{p_i}\right)}(T_{i+1} - T_i) \,. \tag{2}$$

2. Compute the virtual temperatures T^* at all mandatory and significant levels if possible. Then, starting from the surface level, compute the heights for all standard and significant levels assuming a linear variation of the virtual temperature in (ln p) as illustrated in Figure 1:

$$\Delta Z_{i-s} = \frac{R_d}{g} \frac{T_i^* + T_s^*}{2} \ln\left(\frac{p_i}{p_s}\right). \tag{3}$$

3. Winds at the standard pressure levels are interpolated from significant wind data assuming linear variation wind components (u and v) in (ln p) between the significant levels.

4. The recomputed standard pressure level data are compared with the reported standard pressure level data. The limits in Table 12 for the deviations apply. If the differences between the recomputed values and the reported values exceed the limits, the corresponding quality flags are marked as "suspect," *flag = 2*, except for wind direction where the wind quality *flag is incremented by 1.*

5. If a standard pressure level temperature has been flagged "suspect" by the checking procedure, an attempt is made to correct the temperature by changing the sign (i.e., +5°C → −5°C). If the correction gives a temperature within the limits of the recomputed temperature and if the absolute value of the correction is larger than 6°C, a substitution is generated and the original value quality *flag is set to 3.*

6. Missing standard pressure level data are replaced with the recomputed values with the original value retained as missing.

2.5.4 Hydrostatic Consistency of Radiosonde Observations

The hydrostatic equation is used to check the vertical consistency between the reported temperatures and geopotential heights at the standard pressure levels. The hydrostatic equation is one of the most powerful constraints for QC because of two factors: the atmosphere is in approximate hydrostatic balance, and the hydrostatic equation is used to calculate the geopotential heights at the mandatory levels in the original report. Hydrostatic QC is frequently able to produce good substitution for erroneous or missing data by interpolation from observations at the adjacent standard pressure levels. The hydrostatic quality check proceeds in the following steps:

1. The lapse rates between the standard pressure level temperatures are checked by a procedure similar to the one described in section 2.5.2. A slightly superadiabatic lapse rate is allowed; the temperature of any standard pressure level is allowed to be 0.5°C below the temperature, which is extrapolated from below by the dry-adiabatic lapse rate. A temperature exceeding the limits of this check is marked as erroneous, *flag = 3.*

2. If possible, virtual temperatures T^* at the standard pressure levels are computed. From the virtual temperatures (or the air temperatures T), thicknesses (D_i) between the standard pressure levels are computed by assuming a linear variation in (ln p) of the temperatures between the standard pressure levels by

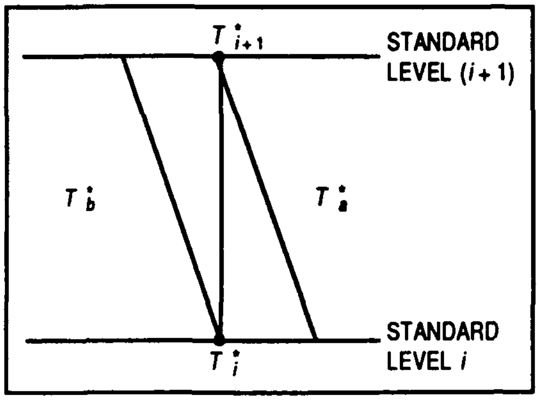

Figure 2. Temperature profile schematic showing warmest (T^*_a) and coldest (T^*_b) possible temperature.

$$D_i = \frac{R_d}{g}\,\frac{T^*_i + T^*_{i+1}}{2}\,\ln\left(\frac{p_i}{p_{i+1}}\right). \qquad (4)$$

3. Tolerances for the deviations between the reported and computed thickness are obtained by considering the most extreme temperature profiles in the layers between the standard pressure levels as shown in Figure 2. T^*_a is the warmest possible temperature profile assuming an inversion at level p_i and a dry adiabatic lapse rate in the layer. T^*_b is the coldest possible temperature profile assuming a dry adiabatic lapse rate in the layer and an inversion at level p_{i+1}. This check is

$$\left|Z_{i+1} - Z_i - D_i\right| < TOL = K\left|\frac{D_a - D_b}{2}\right|, \qquad (5)$$

where, in practice, K is given the value 0.75, since the very extreme temperature profiles T_a and T_b do not occur. The following restrictions on the testing tolerance TOL are used:

- Minimum value of TOL is 20 m.
- Maximum value of TOL is 50 m below 400 mb.
- Maximum value of TOL is 80 m at and above 400 mb.

If the testing algorithm is not fulfilled, the corresponding layer is marked as erroneous, which means that at least one of the values T_i, T_{i+1}, Z_i, or Z_{i+1} must be erroneous.

4. To isolate the errors, the following error index is computed for each error-marked layer:

$$E = \frac{Z_i - Z_{i-1} - D_i}{Z_{i+1} - Z_i - D_i}. \qquad (6)$$

From the value of E, the following conclusions are made:

- $0.5 \le E \le 2.0$: T_i is probably erroneous.
- $-2.0 \le E \le -0.5$: Z_i is probably erroneous.
- $|E| > 2.0$: All heights above Z_i are probably erroneous.
- If $|E| < 5.0$, it is difficult to draw any definite conclusions.

The error-marked heights and temperatures are recomputed from the surrounding level data as described in step 5 for temperatures and step 6 for the heights. The recomputed element is again hydrostatically checked. Temperatures are also checked for extreme lapse rates and inversions. If the datum now satisfies the checking algorithm, the recomputed value is substituted. The original value is always retained with a *flag = 3*.

5. The following methods are used to compute missing or error-marked standard pressure level temperatures. Whenever a standard pressure level temperature has been computed, the resulting lapse rate is checked. If the computed temperature is more than 0.5°C colder or 10°C warmer (extreme inversion) than the temperature obtained by dry adiabatic extrapolation, the computed temperature is error marked.

• If only T_i is missing, compute downward from level $i+1$ by

$$T_i^1 = \frac{2g}{R_d} \frac{Z_{i+1} - Z_i}{\ln\left(\frac{p_{i-1}}{p_i}\right)}, \tag{7}$$

and compute upward from level $i-1$ with

$$T_i^2 = \frac{2g}{R_d} \frac{Z_i - Z_{i-1}}{\ln\left(\frac{p_{i-1}}{p_i}\right)}. \tag{8}$$

If neither temperature fails, the lapse rate check and $|T_i^1 - T_i^2| \le 5°C$, then both temperatures are used to compute an average temperature T_i. If only one temperature is error marked, the nonmarked temperature is used as T_i. When both recomputed temperatures, T_i^1 and T_i^2, are error marked, then

$$T_i = T_{i-1} + \frac{\ln\left(\frac{p_{i-1}}{p_i}\right)}{\ln\left(\frac{p_{i-1}}{p_{i+1}}\right)} (T_{i+1} - T_{i-1}). \tag{9}$$

If this temperature is also error marked, then the temperature T_i cannot be computed.

• If both T_i and Z_i are missing, then

$$T_i = \frac{2g}{R_d} \frac{Z_{i+1} - Z_{i-1}}{\ln\left(\frac{p_{i-1}}{p_{i+1}}\right)} - \frac{T_{i-1} \ln\left(\frac{p_{i-1}}{p_i}\right) + T_{i+1} \ln\left(\frac{p_i}{p_{i+1}}\right)}{\ln\left(\frac{p_{i-1}}{p_{i+1}}\right)}. \tag{10}$$

If T_i is error marked, a new T_i is obtained by equation 9. If neither temperature is approved, the temperature T_i cannot be calculated.

• If T_i and Z_i are missing together with $Z_{i-1,}$ and Z_{i+1}, then T_i is computed by equation 9.

• If T_i, Z_i, and T_{i+1} are missing,

$$T_{i+1} = \frac{2g}{R_d} \frac{Z_{i+1} - Z_{i-1}}{\ln\left(\frac{p_{i-1}}{p_i}\right)} - T_{i-1}, \tag{11}$$

and equation 10 is then used to compute T_i.

• If T_i and T_{i-1} are missing:

$$T_i = \frac{2g}{R_d} \frac{Z_i - Z_{i-2}}{\ln\left(\frac{p_{i-2}}{p_i}\right)} - T_{i+1}. \tag{12}$$

If T_i is error marked, but level $i-2$ is complete and is not error marked, then

$$T_i = \frac{2g}{R_d} \frac{Z_i - Z_{i-2}}{\ln\left(\frac{p_{i-2}}{p_i}\right)} - T_{i-2}. \tag{13}$$

If this T_i is now error marked, the check of level i terminates. The check of level i terminates also if T_{i-2} or Z_{i-2} are missing.

• If T_i and Z_{i-1} are missing,

$$T_i = \frac{2g}{R_d} \frac{Z_{i+1} - Z_i}{\ln\left(\frac{p_i}{p_{i+1}}\right)} - T_{i+1}. \tag{14}$$

If T_i is error marked, a new T_i is computed by equation 9. The check of level i terminates if T_i is error marked again.

• If T_i, Z_{i-1}, and Z_{i+1} are missing, T_i is error marked and the check of level i is terminated.

• If T_i and Z_{i+1} are missing,

$$T_i = \frac{2g}{R_d} \frac{Z_i - Z_{i-1}}{\ln\left(\frac{p_{i-1}}{p_i}\right)} - T_{i-1}. \tag{15}$$

If T_i is error marked, T_i is computed by equation 9. If T_i is error marked again, the check of level i terminates.

• If T_i and T_{i+1} are missing,

$$T_i = \frac{2g}{R_d} \frac{Z_i - Z_{i-1}}{\ln\left(\frac{p_{i-1}}{p_i}\right)} - T_{i-1} . \qquad (16)$$

If T_i is error marked, but T_{i+2} and Z_{i+2} exist (if not, the check of level i terminates), then

$$T_i = \frac{2g}{R_d} \frac{Z_{i+2} - Z_i}{\ln\left(\frac{p_i}{p_{i+2}}\right)} - T_{i+2} . \qquad (17)$$

If T_i is error flagged again, the check of level i terminates.

• If T_i, T_{i+1} and Z_{i+1} are missing, then T_i is computed by equation 16.

• If T_i, T_{i-1} and Z_{i-1} are missing, T_i is calculated by

$$T_i = \frac{2g}{R_d} \frac{Z_i - Z_{i-2}}{\ln\left(\frac{p_{i-2}}{p_i}\right)} - T_{i+1} . \qquad (18)$$

For cases not covered above, the number of missing elements is considered too large, and a reliable computation of the missing temperature cannot be performed.

6. Missing or error-marked height data are computed from above (Z_a) and/or below (Z_b). If possible, virtual temperatures are used for the computation. The following methods apply:

• If only Z_i is missing:

$$Z_b = Z_{i-1} + \frac{R_d}{g}\left(T_i^* + T_{i-1}^*\right) \ln\left(\frac{p_{i-1}}{p_i}\right), \qquad (19)$$

$$Z_a = Z_{i+1} + \frac{R_d}{g}\left(T_i^* + T_{i+1}^*\right) \ln\left(\frac{p_i}{p_{i+1}}\right). \qquad (20)$$

— If $|Z_b - Z_a| \le 30$ gpm, then $Z_i = \frac{1}{2}(Z_b + Z_a)$.

— If $|Z_b - Z_a| > 30$ gpm, but Z_a and Z_b are both accepted by the hydrostatic check of section 2.5.4, then $Z_i = \frac{1}{2}(Z_b + Z_a)$.

— If $|Z_b - Z_a| > 30$ gpm and only Z_b is accepted by the hydrostatic check, $Z_i = Z_b$.

— If $|Z_b - Z_a| > 30$ gpm and only Z_a is accepted by the hydrostatic check, $Z_i = Z_a$.

• If Z_i and data from level $(i - 1)$ are missing, then $Z_i = Z_a$.

• If Z_i and data from level $(i + 1)$ are missing, then $Z_i = Z_b$.

2.5.5 Vertical Wind Shear Checks

The vertical wind shear control is applied for the wind data at standard pressure levels. The shear is checked in two ways:

- A check of the windspeed shear.
- A check of a combination of directional shear and the sum of the windspeeds.

For the check of one standard pressure level wind, one more adjacent standard pressure level wind is needed. A counter system is utilized with four counters for each standard pressure level (SX, SXX, DX, DXX). S and D represent speed and direction, and the number of X's represents the severity. Depending on the results of each test, the counters are updated and the final wind flag for each level is determined.

The speed shear tests are listed.

- $|FF_1 - FF_2| > 20.6 + 0.275\ (FF_1 + FF_2)$ (msec^{-1})
  $SXX_1 = SXX_1 + 1,\ SXX_2 = SXX_2 + 1$
- $|FF_1 - FF_2| > 16.5 + 0.22\ (FF_1 + FF_2)$ (msec^{-1})
  $SX_1 = SX_1 + 1,\ SX_2 = SX_2 + 1$

The directional shear tests are listed.

- $|FF_1 - FF_2| >$ MAXSUM (msec^{-1})
  $DXX_1 = DXX_1 + 1,\ DXX_2 = DXX_2 + 1$
- $|FF_1 - FF_2| > 0.8$ MAXSUM (msec^{-1})
  $DX_1 = DX_1 + 1,\ DX_2 = DX_2 + 1$

Here, MAXSUM depends on the directional shear *DS* between the standard pressure levels and on the pressure level, and is given in Table 13.

Finally, the wind flag for each level is determined by the following sequence of tests:

1. $SX \geq 1$ or $DX \geq 1$ or $SXX \geq 1$ or $DXX \geq 1$ .... *Flag = 1*
2. $SX > 1$ or $DX > 1$ .... *Flag = 2*
3. $SXX > 1$ or $DXX > 1$ .... *Flag = 3*
4. $SX > 1$ or $SXX > 1$ .... *Flag = 3*
5. $DX > 1$ or $DXX > 1$ .... *Flag = 3*

The assumption is made that in the majority of cases, a wind in error at a particular level will exceed the shear limits when compared with the standard pressure levels on both sides of the level, hence, the requirement for the sum of the counters to be greater than 1.

2.6 Pilot Balloon Reports

PIBALs are measurements of windspeed and direction only, as a function of height and/or pressure, with the tracking done optically. The term radiowind, or rawin, is used if the tracking is done electronically.

Table 13. Maximum permitted sum of windspeed (msec^{-1}) for various directional shears between two adjacent standard pressure levels.

LAYER (mb)	<30	≥30	≥40	≥50	≥60	≥70	≥80	≥90
1000–850 850–700 150–100 <100	–	72	61	57	53	49	46	41
All Others	–	110	84	77	70	63	52	50

This section applies to both types of observations. The routines for checking PIBAL data are a subset of those used for radiosonde data (section 2.5). PIBAL wind observations at standard pressure levels undergo the same checks against climatological limits and checks for vertical wind shear as described sections 2.4.1. and 2.5.5.

3.0 Summary

The operational atmospheric data base at FNOC provides quality-controlled observations for use by the Navy's atmospheric analysis and prediction systems. QC is critical, since erroneous observations can adversely affect the quality of the numerical products, which in turn could potentially impact Fleet operations. The objective QC of the meteorological observations is performed prior to storage in the data base and follows the procedures described in this report. A separate report discusses the specific details of the QC system as it is installed at FNOC.

The objective QC compares the observations against gross error limits and evaluates the internal consistency of the report. Radiosonde and PIBAL reports also undergo extensive vertical consistency checks. For radiosondes, the vertical consistency checks include tests for unlikely lapse rates, hydrostatic consistency between reported mandatory pressure levels, and consistency between mandatory and significant pressure levels. Both rawinsonde and PIBAL reports are tested for unrealistic windspeed and directional shears.

Future research efforts will focus on developing innovative QC techniques to handle such problems as the systematic radiative errors in radiosonde geopotential heights and the horizontally correlated errors in the observations derived from the remote sensing of the atmosphere by satellites. Special QC procedures will have to be developed to accommodate the unique errors characteristic of the new observing platforms scheduled for the future.

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3. Abstract *(Maximum 200 words).*

Quality control of meteorological observations is an integral part of atmospheric analysis and prediction, since erroneous observations can dversely impact the accuracy of these environmental products. The meteorological observations are subjected to various validation and error hecks, as described in this report, prior to their storage in an operational atmospheric data base at the Fleet the Numerical Oceanography enter (FNOC). The operational atmospheric data base is used by the Navy's global and regional prediction systems and by the stratospheric nalysis. These models provide direct environmental support for fleet operations worldwide. The same quality control procedures were also sed for the preliminary error checking of many of the observations gathered during the TCM-90 (Tropical Cyclone Motion) experiment. This nitiative, sponsored by the Office of Naval Research, was one component of several joint experiments conducted in the tropical western Pacific cean during the summer of 1990.

The observations that are processed are from a variety of sources. Each observing platform has its own unique error characteristics, which nust be taken into consideration. These sources include observation of pressure, wind and temperature from ships, fixed and drifting buoys, nd land stations. Satellite-based instruments infer atmospheric temperature and moisture profiles, tropospheric wind velocity, and sea-surface vind speeds. Commercial aircraft report air temperature and wind velocity. Perhaps the most important source of information comes from radiosonde nd pilot balloon observations of upper atmosphere temperature, moisture, and wind velocity, profiles. The quality checking procedures for these bservations are derived from a series of rules. Many of the rules are based upon geophysical limitations, such as checks against extreme observed alues and checks for hydrostatic consistency. Other rules stem from required reporting practices. After the quality tests are finished, flags re set for each observation within a report, indicating its assessed quality.

his report describes the quality control of the meteorological observations in the atmospheric data base in sufficient detail to acquaint users f the data of the level of error checking performed prior to storage in the operational atmospheric data base. The majority of the quality checks re sufficiently general so that they could be used for other applications and observation types. Although these checks apply only to meteorological bservations, the same techniques should work for some oceanographic observations as well.

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